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The enclosed summaries provide an outline of some of the URI research projects. In addition to these activities, a scientific meeting combing URI scientists and other distinguished vision researchers in the USA and Canada was organized and held at Boston University in Mar 1988. Members of the URI also played a key role in founding the International Neural Network Society (INNS) and organizing its first annual meeting in Boston on Sep 5-9, 1988, where 600 papers were presented to 1700 participants. Professor Grossberg was INNS President and Professor Carpenter, was the meeting's organization chairman. Professors Carpenter, Cohen Daugman, Grossberg, and Mingolla gave featured lectures. Many additional scientific interactions among URI participants-such as between Arend and Reeves; Arend, Grossberg, and Todorovic'; Grossberg, Reeves, and Rudd; Mingolla and Todd; Arend, Daugman, Mingolla, and Savoy; Richards and Searle; Daugman and Grossberg-were undertaken.

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ANNUAL REPORT

THE COGNITIVE, PERCEPTUAL, AND NEURAL BASES OF SKILLED PERFORMANCE

CONTRACT AFOSR F49620-87-C-0018
OCTOBER 1, 1987—SEPTEMBER 30, 1988

STEPHEN GROSSBERG, PRINCIPAL INVESTIGATOR
CENTER FOR ADAPTIVE SYSTEMS
BOSTON UNIVERSITY
111 CUMMINGTON STREET
BOSTON, MA 02215

INTRODUCTION

The enclosed summaries provide an outline of some of the URI research projects. In addition to these activities, a scientific meeting combining URI scientists and other distinguished vision researchers in the USA and Canada was organized and held at Boston University in March, 1988. Members of the URI also played a key role in founding the International Neural Network Society (INNS) and organizing its first annual meeting in Boston on September 5–9, 1988, where 600 papers were presented to 1700 participants. Professor Grossberg was INNS President and Professor Carpenter was the meeting's organization chairman. Professors Carpenter, Cohen, Daugman, Grossberg, and Mingolla gave featured lectures. Many additional scientific interactions among URI participants—such as between Arend and Reeves; Arend, Grossberg, and Todorović; Grossberg, Reeves, and Rudd; Mingolla and Todd; Arend, Daugman, Mingolla, and Savoy; Richards and Searle; Daugman and Grossberg—were undertaken.

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\+ Also supported in part by the National Science Foundation.

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URI ANNUAL REPORT
Year 2
Gail A. Carpenter
Northeastern University
and
Center for Adaptive Systems

PUBLICATIONS

1. Carpenter, G.A. and Grossberg, S. (1988). The ART of adaptive pattern recognition by a self-organizing neural network. *Computer* (special issue on Artificial Neural Systems), **21**, 77–88.

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3. Carpenter, G.A., Grossberg, S., and Mehanian, C. (1989). Invariant recognition of cluttered scenes by a self-organizing ART architecture, I: CORT-X boundary segmentation. *Neural Networks*, in press.

4. Carpenter, G.A. (1989). Pattern recognition, associative learning, and self-organization. Review article based on tutorial lecture at First Annual INNS Meeting, *Neural Networks*, in preparation.

This portion of the URI contract has led to major progress on Modeling Project 6H (p.47):

H. Modeling Project: Embedding the Coding Module in a Network Hierarchy

The computational principles which enable an ART circuit to do category learning are universal: they are not restricted to particular problem domains, such as speech or vision. For example, a key design constraint is that a pattern should be separable, under appropriate vigilance conditions, from another pattern with which it may share many features (e.g., nested inputs). Once the formal problems listed herein have been solved, ART networks can be used to solve many specialized perceptual and cognitive domains. Indeed, they were originally derived from large data bases within such data domains. In such applications, different preprocessing stages can serve as precursors of the ART input patterns. Neural circuits which generate preattentively completed segmentations of a visual image before these completed segmentations generate inputs to an ART network have recently been constructed (see Section 1). In applications to adaptive speech recognition, inputs are encoded as STM patterns of temporal order information across item representations before these STM patterns generate inputs to an ART network (Appendix 3). Thus, in this stage of the work, we will plug specialized ART circuits into network hierarchies to test their ability to discover, learn, and recognize invariant properties of important classes of vision, speech, and cognitive codes.

Each of the four articles listed above has contributed to this project, as follows.

Article 1 begins with a review of the ART 1 and ART 2 neural network modules that carry out stable self-organization of recognition codes. The article goes on to describe

how an ART module can be embedded in neural network hierarchies for a variety of tasks. These include:

(A) invariant visual pattern recognition, with the ART 2 module attached to a preprocessor that regularizes and completes boundaries and factors out translation, rotation, and scaling invariants;

(B) a neural network hierarchy that incorporates reinforcement and recall, as well as ART recognition; and

(C) a description of a cascade of ART systems embedded in a hierarchy to model the perception and production of speech.

Article 2 solves some key technical difficulties that had stood in the way of moving from the minimal ART 1 and ART 2 designs to more sophisticated network hierarchies. In particular, a new search mechanism allows the ART 2 systems to be naturally embedded into network hierarchies while retaining the basic design of the minimal modules. In particular, the new search mechanism works well in systems with either fast or slow learning and with either compressed or distributed codes. This new search mechanism, as well as the general problem of designing ART systems for neural network hierarchies, is the subject of ongoing research.

Article 3 is the first in a series on the invariant visual pattern recognition problem mentioned above. Article 3 describes a new filter for the preattentive regularization and completion of image boundaries. The CORT-X filter uses multiple scales to carry out many of the computations of the Grossberg-Mingolla Boundary Contour System (BCS), but the feedforward CORT-X filter can allow more rapid computation than does the feedback BCS system, albeit with some loss of pattern processing capabilities.

Article 4 is primarily a review article describing the history of neural networks for pattern recognition, associative learning, and self-organization. However, being organized by theme rather than chronology, the article leads naturally to a new system that incorporates two or more ART 2 modules into a network hierarchy for associative learning.

URI ANNUAL REPORT
Year 2
Ennio Mingolla
Center for Adaptive Systems

Modeling Project: 3-D Shape from 2-D Images of Surfaces

Software has been developed on a Silicon Graphics IRIS 3130 workstation to rapidly generate parametrically varied families of srufaces illuminated by single or multiple light sources. New graduate students in the Cognitive and Neural Systems Program are learning about the BCS in anticipation of carrying out simulations of multiple-scale boundary webs.

Experiments on Surface Perception

Since the arrival and installation of the Silicon Graphics IRIS 3130 workstation in June, 1987, Dr. Mingolla has developed number of software tools for manipulating surface reflectance characteristics of simulated surafces. The shading model of equation (1) (page 26) has been implemented, along with some special techniques for introducing smooth nonlinear distortions of certain image pixel intensities. As a result, surface appearance can be controlled either by conventional computer graphics techniques (the shading model equation) or by manipulations having no analog in the natural image generation process. The latter manipulations, however, enable testing of theoretical ideas. Thus, following implications/predictions of the theory of Grossberg and his colleagues, he was able to construct a display in which one half of an extended surface could be made to appear either glossy or dull *without any change of its pixel intensities.* Instead, the context of adjacent pixel intensities was manipulated by nonlinear distortions in such a way that a certain portion of the unchanged surface would in one case be processed as *structural* (i.e., part of a boundary web) and in another case as featural (i.e., part of FCS spreading). In the former case the unchanged region appeared dull, in the latter case shiny.

Preliminary results from this research were reported at the Fourth International Conference on Event Perception, Trieste, Italy, August 1987, and additional work was presented at a topical meeting on Shape-from-Shading in the fall of 1988 in Toronto, Canada. A more sophisticated version of the nonlinear intensity manipulation scheme is being developed.

Publications and Conference Presentations

Grossberg, S., Mingolla, E., and Todorović, D.: A neural network architecture for general-purpose preattentive vision. *IEEE Transactions on Biomedical Engineering*, in press, 1988.

Mingolla, E.: Recent results in emergent visual segmentation. Presented at a topical meeting: "Visual Form and Motion Perception: Psychophysics, Computation, and Neural Networks." Boston, March, 1988.

Mingolla, E.: Context-sensitive noise suppression and regularization in a neural network model of preattentive visual segmentation (with Stephen Grossberg). Poster given at the 1988 annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Florida.

Mingolla, E.: Recent results in emergent visual segmentation. Invited talk at the First Annual Meeting of the International Neural Network Society, Boston, September, 1988.

Mingolla, E.: Distinguishing form from highlights. Invited talk at a topical meeting on Shape-from-Shading, Scarborough College, Toronto, September, 1988.

URI Annual Report. 9/20/1988

Adam Reeves
Dept. of Psychology, Northeastern University, Boston Mass 02115.

The proposed work concerned the mechanisms underlying perception of color.

I Mondrian displays.

We have completed five studies of color constancy in Land-type 'Mondrian' displays; that is, displays of several abutted homogeneous colored 'papers', which in our work have been simulated on a high-resolution color monitor. This work has been done with L. E. Arend of the Eye Research Institute, as part of the URI grant. Observers are required to make matches between standard and comparison displays lit (in the simulation) by different phases of daylight. We ask whether color constancy can be obtained (i.e., whether the matches would be independent of illuminant.) Our studies feature (1) control of adaptational state; (2) control of the observer's task (to match surface appearances, or to match chromaticities); (3) control of stimulus complexity (annular versus Mondrian-type displays); (4) use of standard and comparison stimuli with the same surrounds, to avoid unequal induction; (5) use of binocular vision, to avoid the standard haploscopic method in which standard and comparison are presented to different eyes and so fall on differently-adapted retinae.

Results of Study 1 (supported by previous grants) show that when the state of adaptation is kept roughly constant by requiring the observer to scan back and forth between comparison and standard displays, the extent of color constancy depends primarily on instruction and only very secondarily on stimulus complexity (Arend and Reeves, 1986). Color constancy is strong with surface appearance ('paper') matches, but weak or absent in chromaticity ('hue and saturation') matches. This important result is contrary to many established models for color constancy (eg, Retinex).

New work, done under the URI grant (first and second years) and partly reported at ARVO (Arend, et. al., 1987; 1988) shows that the same surprising pattern of results is obtained when luminance variations of up to 19:1 are added to the displays (Study 2; near equi-luminance displays were used in Study 1).

We also find this pattern of results when standard and comparison displays are alternated (Study 3), rather than being presented simultaneously as in Study 1. This is important because color constancy would not be expected across two simultaneous displays if the visual system extracted a mean illuminant over the entire visual field. Therefore, the absence of color constancy in the chromaticity task even in this experiment is particularly significant.

In Study 4, we have found color constancy for the chromaticity instruction, when adaptation is appropriately varied by interposing homogeneous adapting fields between stimulus presentations. This result would be expected from Von Kries -type considerations and serves as a control on our methods.

In Study 5, we asked subjects to set a single target paper in a single Mondrian to a specified unique color (eg, yellow). Once more,

we have found a large effect of instructions: color constancy is good in the paper task, but not in the chromaticity task. This result is important, because one might have argued that a form of temporal integration (as well as spatial) across displays occurred in Study 3, once gain preventing color constancy even though the displays in Study 3 were alternated. Study 5 controlled for this because only one display is seen in each block of trials.

We have developed an index for color constancy in order to quantify its extent. On (u′, v′) CIE co-ordinates, which are approximately equally-spaced in jnd.s, we let c= the distance from the test co-ordinate to the match coordinate divided by the distance that would be found if color constancy were perfect. We then average the values of c found for the five different test chromaticities that we use (red, green, yellow, grey, and blue). Mean c equals 1.0 if color constancy is perfect, and =0 if subjects make chromaticity matches (and thus show no color constancy). Over all conditions and subjects, we find mean c = 0.6 for surface matches and for chromaticity matches. These values for c vary little over experiments, though they do vary over subjects; our 'worst' subject in the paper match averaged c=0.4 (but he also obtained c=.2 in the chromaticity matches).

II. Adaptational history.

We have tested, calibrated, and programmed our Generation V SRI Purkinje Eye-tracker, in order to study the effect of the adaptational history of an observer whose eyes are free to scan the display naturally. We proposed a series of experiments based on this technology in the original URI grant. However, the work has gone very slowly, partly due to technical problems with the Eye tracker, which have been fixed. As yet we have no publishable data, but we have made useable recordings. We plan to perform the proposed experiments in the third year of the grant.

III. Depth, lightness, and brightness.

In separate work with achromatic displays which simulate experiments first done by Alan Gilchrist (1977), we have found that perceived depth influences the lightness, but not the brightness, of a target. (Gilchrist did not make this distinction operationally.)

The target is surrounded by surfaces which, due to interposition and/or stereo cues, appear in different depth planes (Schirillo, 1987; Reeves and Schirillo, 1987). Subjects match either the lightness or the brightness of a target area to a Munsell scale presented below the screen. This work has been done with moderate, large, and very large (900:1) contrast ratios (the latter like Gilchrist's). We have varied the background of the Munsell scale and the method of matching (multiple choice or adjustment). In each case, depth has no effect on brightness, but changes the Munsell value by up to 3 points. The reliability of this finding suggests that brightness is computed before, and lightness after, the construction of a 3-D representation of the image. This work was completed in the second year of the URI grant and is being written up for publication.

These studies have been conducted with Lawrence Arend of the Eye Research Institute, and James Schirillo, who is a PhD student at Northeastern, both supported by the URI grant.

IV. Transient tritanopia

During the second year of the grant period, work has been done with Michael Rudd and Steven Grossberg (Center for Adaptive Systems) to model earlier work on transient tritanopia and its analogues in the red/green system. The essential finding is that turning off or down a colored background can greatly reduced the sensitivity of the red/green and yellow/blue hue pathways, even though normal dark adaptation (recovery of sensitivity) occurs in the luminance channel. The current best model for this, by Pugh and Mollon, postulates a slow (15 sec time-constant) 'restoring force' which builds up during light adaptation and suddenly rebounds when the light is turned off. This model, however, cannot handle the result (of Reeves) that transient tritanopia can be completely eliminated by 1 Hz flicker during the adaptation period. The new model (Reeves, 1988) employs Grossberg's theoretical circuits which can predict the relevant phenomena qualitatively. We are currently refining the model and attempting to broaden the logical and empirical support for it.

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L E Arend, A Reeves, "Simultaneous color constancy" J.O.S.A. (A),3, 1743-1751, 1986.

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L E Arend, A Reeves, J Schirillo, R Goldstein "Simultaneous color constancy; Patterns with diverse Munsell values" Submitted for publication (1988).

A Reeves, J Schirillo "Depth, Lightness, and Brightness of achromatic surfaces" Paper given at the Annual meeting of the Optical Soc. of Am., Oct 22, 1987, in Rochester N.Y.

J Schirillo "Perceived depth influences lightness and brightness of achromatic surfaces". Northeastern University: MA Thesis, 1987.

A Reeves "Fundamental mechanisms of color vision" Paper given at the meeting "Visual form and motion perception: psychopysics, computation, and neural networks" , Boston University, March 1988.

A Reeves, L E Arend, and J Schirillo. "Simultaneous and successive color constancy." Invest. Ophthal. Vis. Sci. 29, 162, 1988.

Traditional Form and Motion Stimuli Presented to Isolated Cone Classes

Robert L. Savoy and **Michael M. Burns**

Rowland Institute for Science
100 Cambridge Parkway
Cambridge, MA 02142

Two ideas are explored, both of which concern the organization of cone classes in the subsequent connections of the visual system.

1: *The simplest notion of isoluminance is problematic.* If isoluminance is determined by a weighted sum of the input from individual cone classes then all the phenomena reported to occur with isoluminant stimuli should be present whatever the spectral composition of the colors used. Thus, for example, the disappearance of the kinetic depth effect should occur equally well using green dots on a grey background or green dots on a red background. Our work demonstrates that this is not the case. Using both subjective and objective criteria, the quality of isoluminance matches (and the psychophysical phenomena associated with isoluminant stimuli) vary dramatically with the spectral composition of the colored stimuli. The subjective measure is simply the reported quality of match. The objective measure is the variability of isoluminance settings. In particular, when the colors are a grey and green, the accuracy (repeatability) of isolumance matches is extremely good—about 1% (as good as making a luminance match with a single hue). And subjects experience the match as being excellent—in the case of the kinetic depth effect, all sense of depth is lost at isoluminance. On the other hand, when the colors are a saturated red and saturated blue, the variability of isoluminance settings is much higher—about 15%. The subjective phenomena are much weaker as well. Subjects continue to experience such phenomena as the kinetic depth effect at all relative settings of the two colors (in contrast to some reports). This finding is robust across a number of criteria—the kinetic depth effect, stereopsis, hetereochromatic brightness matches, and flicker.

2: *It is possible (using computer generated stimuli) to present a broad range of traditional psychophysical stimuli so that only a single class of cones can be used in the perception of those stimuli.* This is an extension of the body of work done using the "cardinal" directions of color space, to use the term coined by Krauskopf, et al. Stimuli are designed so that the spatial and temporal pattern on (for instance) two of the three cone classes is uniform. The third cone class is presented with spatial and temporal patterns of arbitrary complexity. The simplest experiment is to measure the contrast threshold for detection of a spot by a single cone class. The results (which replicate the work of several other laboratories) reveal the cardinal directions to be one luminance-like channel and two color difference channels. More general stimuli are possible. For instance, one can present a random dot stereogram so that the pattern on the left eye is seen only by the long-wave cones while the pattern on the right eye is seen only by the middle wave cones. Stereopsis is still obtained (and can be quantitatively assessed, in terms of the contrast needed to be perceived). More than one intensity level can be presented at once, so that Mach Band patterns, Simultaneous Contrast patterns, and even Mondrian-like patterns can be presented to isolated cone classes. The only restriction is that the maximum contrast cannot be too large—about 15% on the long and middle wave cone classes and about 80% on the short wave cones. This limitation is imposed by the overlap of the cone pigment absorptions. These techniques for isolating the activities of cone classes have already been used in some neurophysiological work and promise to be a useful tool in determining connections in the visual system.

Presented Saturday, March 5, 1988, at Boston University.

URI ANNUAL REPORT
Year 2
James T. Todd
Brandeis University
and
Center for Adaptive Systems

PUBLICATIONS

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Fetters, L.E. and Todd, J.T. (1987). Quantitative assessment of infact reaching movements. *Journal of Motor Behavior*, **19**, 147–166.

Reichel, F.D. and Todd, J.T. (1988). Perceived depth reversals of smoothly curved surfaces from changes in image orientation. *Journal of Experimental Psychology: Human Perception and Performance*, submitted for publication.

Todd, J.T. (1988). Perceived 3D structure from 2-frame apparent motion. *Investigative Ophthalmology*, **29**, 265.

Todd, J.T. and Akerstrom, R.A. (1987). The perception of three dimensional form from patterns of optical texture. *Journal of Experimental Psychology: Human Perception and Performance*, **2**, 242–255.

Todd, J.T., Akerstrom, R.A., Reichel, F.D., and Hayes, W. (1988). Apparent rotation in 3-dimensional space: Effects of temporal, spatial, and structural factors. *Perception and Psychophysics*, **43**, 179–188.

Todd, J.T. and Reichel, F.D. (1988). Ordinal structure in the visual perception and cognition of smoothly curved surfaces. *Psychological Review*, submitted for publication.

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Perception of shape from shading. Vanderbilt University, January, 1987.

Perception of structure form motion. Boston University, March, 1987.

Apparent motion in three-dimensional space. New York University, April, 1987.

Perception of smoothly curved surfaces. Meeting of the Society for Ecological Psychology, Atlanta, Georgia, May, 1987.

Perception of smoothly curved surfaces. Harvard University, November, 1987.

Perception of smoothly curved surfaces. University of California, San Diego, November, 1987.

Perception of smoothly curved surfaces. University of California, Irvine, November, 1987.

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Perception of smoothly curved surfaces. Johns Hopkins University, December, 1987.

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Perceived 3D structure from 2-frame apparent motion. Meeting of ARVO, Sarasota, Florida, May, 1988.

Ordinal structure from shading. Conference on Vision and Shape from Shading, Toronto, Canada, September, 1988.

Visual perception of structure from motion. Boston University, November, 1988.

Minimal conditions for the perception of structure from motion. Meeting of the Psychonomic Society, Chicago, Illinois, November, 1988.

THE PERCEPTION OF STEREOSCOPIC TRANSPARENCY

Robin A. Akerstrom and James T. Todd
Brandeis University
Waltham, Massachusetts

Perception and Psychophysics, 1988, **44**, 421–432

The research in the present article was designed to investigate the phenomenon of stereoscopic transparency, in which overlapping surfaces are perceived simultaneously at different depths in the same visual direction. Four experiments are reported that examined observers' abilities to achieve this phenomenon over a wide range of stimulus conditions. The results indicate that (1) the perceptual segregation of overlapping transparent surfaces is significantly more difficult that are comparable judgments for opaque surfaces; (2) the perception of transparency is impaired by increased depth differences between the overlapping surfaces or by increased element density; and (3) the effect is facilitated when the overlapping depth planes are distinguished by color, but not when they are distinguished by element orientation. The theoretical significance of these results is considered within the context of current competitive/cooperative models of stereo matching.

This research was supported in part by the Air Force Office of Scientific Research (F49620-87-C-0018) and a joint grant from the Office of Naval Research and the National Science Foundation (BNS-8420143).

PERCEIVED DEPTH INVERSION OF SMOOTHLY CURVED SURFACES

Francene D. Reichel and James T. Todd
Brandeis University
Waltham, Massachusetts

Journal of Experimental Psychology: Human Perception and Performance, submitted, 1988

Perceptual depth inversion of smoothly curved surfaces was investigated in two experiments. Observers made relative depth judgments for pairs of points on three computer generated surfaces that were presented in two orientations—upright and upside down. The same three surfaces were defined by shading in the first experiment, and by contours in the second experiment. The results of the experiments indicate that: (a) For both shaded and contoured depictions of smoothly curved surfaces, a 180-degree rotation in the picture plane causes perceptual reversals such that some regions of the undulating surfaces appear to reverse in depth. (b) Smoothly curved surfaces do not reverse as wholes. Rather, they undergo a piecemeal reversal, where certain local regions reverse in depth, and others remain stable. (c) Some surfaces are more susceptible to perceptual reversal than others. (d) The presence of occlusion contours decreases the likelihood of perceptual reversals.

This research was supported in part by the Air Force Office of Scientific Research (F49620-87-C-0018) and a joint grant from the Office of Naval Research and the National Science Foundation (BNS-8420143).

PERCEPTION OF THREE-DIMENSIONAL FORM FROM PATTERNS OF OPTICAL TEXTURE

James T. Todd and Robin A. Akerstrom
Brandeis University
Waltham, Massachusetts

Journal of Experimental Psychology: Human Perception and Performance, 1987, **13**, 242–255

The research described in the present article was designed to investigate how patterns of optical texture provide information about the three-dimensional structure of objects in space. Four experiments were performed in which observers were asked to judge the perceived depth of simulated ellipsoid surfaces under a variety of experimental conditions. The results revealed that (a) judged depth increases linearly with simulated depth although the slope of this relation varies significantly among different types of texture patterns. (b) Random variations in the sizes and shapes of individual surface elements have no detectable effect on observers' judgments. (c) The perception of three-dimensional form is quite strong for surfaces displayed under parallel projection, but the amount of apparent depth is slightly less than for identical surfaces displayed under polar projection. (d) Finally, the perceived depth of a surface is eliminated if the optical elements in a display are not sufficiently elongated or if they are not approximately aligned with one another. A theoretical explanation of these findings is proposed based on the neural network analysis of Grossberg and Mingolla.

This research was supported in part by the Air Force Office of Scientific Research (F49620-87-C-0018) and a joint grant from the Office of Naval Research and the National Science Foundation (BNS-8420143).

APPARENT ROTATION IN THREE-DIMENSIONAL SPACE: EFFECTS OF TEMPORAL, SPATIAL, AND STRUCTURAL FACTORS

James T. Todd, Robin A. Akerstrom, and Francene D. Reichel
Brandeis University
Waltham, Massachusetts
and
William Hayes
Albion College
Albion, Michigan

Perception and Psychophysics, 1988, **43**, 179–188

Several experiments were performed in an effort to determine the different combinations of display parameters that can reliably elicit a perceptually compelling impression of a solid object rotating rigidly in three-dimensional space. All of the displays were computer-generated simulations of rigid objects rotating in depth under parallel projection. The parameters investigated included the number of frames in the apparent motion sequence, the temporal and spatial displacements between frames, the number of elements in the depicted object, and the structural organization of those elements. The results indicated that there are large interactions among these different parameters in their effects on the perception of structure from motion.

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ORDINAL STRUCTURE IN THE VISUAL PERCEPTION AND COGNITION OF SMOOTHLY CURVED SURFACES

James T. Todd and Francene D. Reichel
Brandeis University
Waltham, Massachusetts

Psychological Review, submitted, 1988

In theoretical analyses of visual form perception, it is often assumed that the 3-dimensional structures of smoothly curved surfaces are perceptually represented as point-by-point mappings of metric depth and/or orientation relative to the observer. This paper describes an alternative theory, in which it is argued that our visual knowledge of smoothly curved surfaces is often restricted to local, nonmetric order relations. A fundamental prediction of this analysis is that relative depth judgments between any two surface regions should be dramatically influenced by the monotonicity of depth change (or lack of it) along the intervening portions of the surface through which they are separated. This prediction is confirmed in a series of experiments using surfaces depicted with either shading or texture. Additional experiments are reported, moreover, which demonstrate that smooth occlusion contours are a primary source of information about the ordinal structure of a surface, and that the depth extrema in between contours can be optically specified by differences in luminance at the points of occlusion.

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ABSTRACTS OF SELECTED ARTICLES FROM THE CENTER FOR ADAPTIVE SYSTEMS

PROBING COGNITIVE PROCESSES THROUGH THE STRUCTURE OF EVENT-RELATED POTENTIALS DURING LEARNING: AN EXPERIMENTAL AND THEORETICAL ANALYSIS

Jean-Paul Banquet† and Stephen Grossberg‡

Applied Optics, 1987, **26**, 4931–4946

ABSTRACT

Data reporting correlated changes, due to learning, in the amplitudes and chronometry of several event related potentials (ERPs) are compared with neural explanations and predictions of the *adaptive resonance theory.* The ERP components processing negativity (PN), early positive wave (P120), N200, and P300 covary with model processes of attentional priming and top-down expectancy learning, matching of bottom-up input patterns with learned top-down expectations, mismatch-mediated activation of the orienting subsystem, reset by the orienting subsystem of recognition codes in short term memory, and direct activation of recognition codes via a bottom-up adaptive filter. These model mechanisms enable a recognition code to be learned in a self-stabilizing fashion in response to an input environment of arbitrary complexity. Thus spatiotemporal correlations among several ERPs during learning provide important evidence in support of postulated neural mechanisms for self-stabilizing self-organization of cognitive recognition codes.

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NEURAL DYNAMICS OF PLANNED ARM MOVEMENTS: EMERGENT INVARIANTS AND SPEED-ACCURACY PROPERTIES DURING TRAJECTORY FORMATION

Daniel Bullock† and Stephen Grossberg‡

Psychological Review, 1988, 95, 49–90

ABSTRACT

A real-time neural network model, called the Vector Integration to Endpoint, or VITE, Model, is developed and used to quantitatively simulate behavioral and neural data about planned and passive arm movements. Invariants of arm movements emerge through network interactions rather than through an explicitly precomputed trajectory. Motor planning occurs in the form of a Target Position Command, or TPC, which specifies where the arm intends to move, and an independently controlled GO command, which specifies the movement's overall speed. Automatic processes convert this information into an arm trajectory with invariant properties. These automatic processes include computation of a Present Position Command, or PPC, and a Difference Vector, or DV. The DV is the difference of the PPC and the TPC at any time. The PPC is gradually updated by integrating the DV through time. The GO signal multiplies the DV before it is integrated by the PPC. The PPC generates an outflow movement command to its target muscle groups. Opponent interactions regulate the PPC's to agonist and antagonist muscle groups. This system generates synchronous movements across synergetic muscles by automatically compensating for the different total contractions that each muscle group must undergo. Quantitative simulations are provided of Woodworth's Law, of the speed-accuracy trade-off known as Fitts' Law, of isotonic arm movement properties before and after deafferentation, of synchronous and compensatory "central error correction" properties of isometric contractions, of velocity amplification during target switching, of velocity profile invariance and asymmetry, of the changes in velocity profile asymmetry at higher movement speeds, of the automatic compensation for staggered onset times of synergetic muscles, of vector cell properties in precentral motor cortex, of the inverse relationship between movement duration and peak velocity, and of peak acceleration as a function of movement amplitude and duration. It is shown that TPC, PPC, and DV computations are needed to actively modulate, or gate, the learning of associative maps between TPC's of different modalities, such as between the eye-head system and the hand-arm system. By using such an associative map, looking at an object can activate a TPC of the hand-arm system, as Piaget noted. Then a VITE circuit can translate this TPC into an invariant movement trajectory. An auxiliary circuit, called the Passive Update of Position, or PUP, Model, is described for using inflow signals to update the PPC during passive arm movements due to external forces. Other uses of outflow and inflow signals are also noted, such as for adaptive linearization of a nonlinear muscle plant, and sequential read-out of TPC's during a serial plan, as in reaching and grasping. Comparisons are made with other models of motor control, such as the mass-spring and minimum-jerk models.

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ART 2: SELF-ORGANIZATION OF STABLE CATEGORY RECOGNITION CODES FOR ANALOG INPUT PATTERNS

Gail A. Carpenter† and Stephen Grossberg‡

Applied Optics, 1987, **26**, 4919–4930

ABSTRACT

Adaptive resonance architectures are neural networks that self-organize stable pattern recognition codes in real-time in response to arbitrary sequences of input patterns. This article introduces ART 2, a class of adaptive resonance architectures which rapidly self-organize pattern recognition categories in response to arbitrary sequences of either analog or binary input patterns. In order to cope with arbitrary sequences of analog input patterns, ART 2 architectures embody solutions to a number of design principles, such as the stability-plasticity tradeoff, the search-direct access tradeoff, and the match-reset tradeoff. In these architectures, top-down learned expectation and matching mechanisms are critical in self-stabilizing the code learning process. A parallel search scheme updates itself adaptively as the learning process unfolds, and realizes a form of real-time hypothesis discovery, testing, learning, and recognition. After learning self-stabilizes, the search process is automatically disengaged. Thereafter input patterns directly access their recognition codes without any search. Thus recognition time for familiar inputs does not increase with the complexity of the learned code. A novel input pattern can directly access a category if it shares invariant properties with the set of familiar exemplars of that category. A parameter called the attentional vigilance parameter determines how fine the categories will be. If vigilance increases (decreases) due to environmental feedback, then the system automatically searches for and learns finer (coarser) recognition categories. Gain control parameters enable the architecture to suppress noise up to a prescribed level. The architecture's global design enables it to learn effectively despite the high degree of nonlinearity of such mechanisms.

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A MASSIVELY PARALLEL ARCHITECTURE FOR A SELF-ORGANIZING NEURAL PATTERN RECOGNITION MACHINE

Gail A. Carpenter† and Stephen Grossberg‡

Computer Vision, Graphics, and Image Processing, 1987, **37**, 54–115

ABSTRACT

A neural network architecture for the learning of recognition categories is derived. Real-time network dynamics are completely characterized through mathematical analysis and computer simulations. The architecture self-organizes and self-stabilizes its recognition codes in response to arbitrary orderings of arbitrarily many and arbitrarily complex binary input patterns. Top-down attentional and matching mechanisms are critical in self-stabilizing the code learning process. The architecture embodies a parallel search scheme which updates itself adaptively as the learning process unfolds. After learning self-stabilizes, the search process is automatically disengaged. Thereafter input patterns directly access their recognition codes without any search. Thus recognition time does not grow as a function of code complexity. A novel input pattern can directly access a category if it shares invariant properties with the set of familiar exemplars of that category. These invariant properties emerge in the form of learned critical feature patterns, or prototypes. The architecture possesses a context-sensitive self-scaling property which enables its emergent critical feature patterns to form. They detect and remember statistically predictive configurations of featural elements which are derived from the set of all input patterns that are ever experienced. Four types of attentional process—priming, gain control, vigilance, and intermodal competition—are mechanistically characterized. Top-down priming and gain control are needed for code matching and self-stabilization. Attentional vigilance determines how fine the learned categories will be. If vigilance increases due to an environmental disconfirmation, then the system automatically searches for and learns finer recognition categories. A new nonlinear matching law (the 2/3 Rule) and new nonlinear associative laws (the Weber Law Rule, the Associative Decay Rule, and the Template Learning Rule) are needed to achieve these properties. All the rules describe emergent properties of parallel network interactions. The architecture circumvents the noise, saturation, capacity, orthogonality, and linear predictability constraints that limit the codes which can be stably learned by alternative recognition models.

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SPEECH PERCEPTION AND PRODUCTION BY A SELF-ORGANIZING NEURAL NETWORK

Michael A. Cohen, Stephen Grossberg, and David G. Stork

In **Evolutior, Learning, Cognition, and Advanced Architectures**
Y.C. Lee (Ed.), Hong Kong: World Scientific, 1988

ABSTRACT

Considerations of the real-time self-organization of neural networks for speech recognition and production have lead to a new understanding of several key issues in such networks, most notably a definition of new processing units and functions of hierarchical levels in the auditory system. An important function of a particular neural level in the auditory system is to provide a partially-compressed code, mapped to the articulatory system, to permit imitation of novel sounds. Furthermore, top-down priming signals from the articulatory system to the auditory system help to stabilize the emerging auditory code. These structures help explain results from the motor theory, which states that speech is analyzed by how it would be produced. Higher stages of processing require chunking or unitization of the emerging language code, an example of a classical grouping problem. The partially compressed auditory codes are further compressed into item codes (e.g., phonemic segments), which are stored in a working memory representation whose short-term memory pattern is its code. A masking field level receives input from this working memory and encodes this input into list chunks, whose top-down signals organize the items in working memory into coherent groupings with invariant properties. This total architecture sheds new light on key speech issues such as coarticulation, analysis-by-synthesis, motor theory, categorical perception, invariant speech perception, word superiority, and phonemic restoration.

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CONTENT-ADDRESSABLE MEMORY STORAGE BY NEURAL NETWORKS: A GENERAL MODEL AND GLOBAL LIAPUNOV METHOD

Stephen Grossberg†

In E.L. Schwartz (Ed.), **Computational Neuroscience**
Cambridge, MA: MIT Press, 1987

ABSTRACT

Many neural network models capable of content-addressable memory are shown to be special cases of the general model and global Liapunov function described by Cohen and Grossberg (1983). These include examples of the additive, brain-state-in-a-box, McCulloch-Pitts, Boltzmann machine, shunting, masking field, bidirectional associative memory, Volterra-Lotka, Gilpin-Ayala, and Eigen-Schuster models. The Cohen-Grossberg model thus defines a general principle for the design of content-addressable networks. A model-independent property, such as content-addressable memory, that is shared by all model exemplars of such a general design constitutes a computational invariant. Such a general model and analytic method defines a computational framework within which specialized model exemplars may be compared to discover which models are best able to explain particular parametric data about brain and behavior, or to solve particular technological problems.

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NONLINEAR NEURAL NETWORKS: PRINCIPLES, MECHANISMS, AND ARCHITECTURES

Stephen Grossberg‡

Neural Networks, 1988, 1, 17–61

ABSTRACT

An historical discussion is provided of the intellectual trends that caused 19th century interdisciplinary studies of physics and psychobiology by leading scientists such as Helmholtz, Maxwell, and Mach to splinter into separate 20th century scientific movements. The nonlinear, nonstationary, and nonlocal nature of behavioral and brain data are emphasized. Three sources of contemporary neural network research—the binary, linear, and continuous-nonlinear models—are noted. The remainder of the article describes results about continuous-nonlinear models: Many models of content-addressable memory are shown to be special cases of the Cohen-Grossberg model and global Liapunov function, including the additive, brain-state-in-a-box, McCulloch-Pitts, Boltzmann machine, Hartline-Ratliff-Miller, shunting, masking field, bidirectional associative memory, Volterra-Lotka, Gilpin-Ayala, and Eigen-Schuster models. A Liapunov functional method is described for proving global limit or oscillation theorems for nonlinear competitive systems when their decision schemes are globally consistent or inconsistent, respectively. The former case is illustrated by a model of a globally stable economic market, and the latter case is illustrated by a model of the voting paradox. Key properties of shunting competitive feedback networks are summarized, including the role of sigmoid signalling, automatic gain control, competitive choice and quantization, tunable filtering, total activity normalization, and noise suppression in pattern transformation and memory storage applications. Connections to models of competitive learning, vector quantization, and categorical perception are noted. Adaptive resonance theory (ART) models for self-stabilizing adaptive pattern recognition in response to complex real-time nonstationary input environments are compared with off-line models such as autoassociators, the Boltzmann machine, and back propagation. Special attention is paid to the stability and capacity of these models, and to the role of top-down expectations and attentional processing in the active regulation of both learning and fast information processing. Models whose performance and learning are regulated by internal gating and matching signals, or by external environmentally generated error signals, are contrasted with models whose learning is regulated by external teacher signals that have no analog in natural real-time environments. Examples from sensory-motor control of adaptive vector encoders, adaptive coordinate transformations, adaptive gain control by visual error signals, and automatic generation of synchronous multijoint movement trajectories illustrate the former model types. Internal matching processes are shown capable of discovering several different types of invariant environmental properties. These include ART mechanisms which discover recognition invariants, adaptive vector encoder mechanisms which discover movement invariants, and autoreceptive associative mechanisms which discover invariants of self-regulating target position maps.

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NEURAL DYNAMICS OF DECISION MAKING UNDER RISK: AFFECTIVE BALANCE AND COGNITIVE-EMOTIONAL INTERACTIONS

Stephen Grossberg† and William Gutowski

Psychological Review, 1987, **94**, 300–318

ABSTRACT

A real-time neural network model, called Affective Balance Theory, is developed to explain many properties of decision making under risk which heretofore have been analysed using formal algebraic models, notably Prospect Theory. The model describes cognitive-emotional interactions which are designed to ensure adaptive responses to environmental demands, but whose emergent properties nonetheless can lead to paradoxical and even irrational decisions in risky environments. Emotional processing in the model is carried out by an opponent processing network, called a *gated dipole*. Learning enables cognitive representations to generate affective reactions of the dipole. Habituating chemical transmitters within a gated dipole determine an affective adaptation level, or context, against which later events are evaluated. Neutral events can become affectively charged either through direct activations or antagonistic rebounds within a previously habituated dipole. The theory describes the affective consequences of strategies in which an individual compares pairs of events or statements that are not necessarily explicitly grouped within the stimuli. The same preference orders may sometimes, but not always, emerge from different sequences of pairwise alternatives. The role of short term memory updating and expectancy-modulated matching processes in regulating affective reactions is described. The formal axioms of Prospect Theory are dynamically explicated through this analysis. Analyses of judgments of the utility of a single alternative, choices between pairs of regular alternatives, choices between riskless and risky alternatives, and choices between pairs of risky alternatives lead to explanations of such phenomena as preference reversals, gambler's fallacy, framing effect, and the tendency towards risk aversion when gains are involved but risk taking when losses are involved. These explanations illustrate that data concerning decision making under risk may now be related to data concerning the dynamics of conditioning, cognition, and emotion as consequences of a single psychophysiological theory.

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NEURAL DYNAMICS OF ATTENTIONALLY MODULATED PAVLOVIAN CONDITIONING: BLOCKING, INTER-STIMULUS INTERVAL, AND SECONDARY REINFORCEMENT

Stephen Grossberg† and Daniel S. Levine

Applied Optics, 1987, **26**, 5015–5030

ABSTRACT

Selective information processing in neural networks is studied through computer simulations of Pavlovian conditioning data. The model reproduces properties of blocking, inverted-U in learning as a function of interstimulus interval, anticipatory conditioned responses, secondary reinforcement, attentional focussing by conditioned motivational feedback, and limited capacity short-term memory parocessing. Conditioning occurs from sensory to drive representations ("conditioned reinforcer" learning), from drive to sensory representations ("incentive motivational" learning), and from sensory to motor representations ("habit" learning). The conditionable pathways contain long-term memory traces that obey a non-Hebbian associative law. The neural model embodies a solution to two key design problems of conditioning, the synchronization and persistence problems. This model of vertebrate learning is compared with data and models of invertebrate learning. Predictions derived from models of vertebrate learning are compared with data about invertebrate learning, including data from *Aplysia* about facilitator neurons and data from *Hermissenda* about voltage-dependent Ca^{++} currents. A prediction is stated about classical conditioning in all species, called the Secondary Conditioning Alternative, and if confirmed would constitute an evolutionary invariant of learning.

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PREDICTIVE REGULATION OF ASSOCIATIVE LEARNING IN A NEURAL NETWORK BY REINFORCEMENT AND ATTENTIVE FEEDBACK

Stephen Grossberg† and Daniel Levine and Nestor Schmajuk‡

To appear in a special issue on Memory of the
International Journal of Neurology, in press, 1988

ABSTRACT

A real-time neural network model is described in which reinforcement helps to focus attention upon and organize learning of those environmental events and contingencies that have predicted behavioral success in the past. Computer simulations of the model reproduce properties of attentional blocking, inverted-U in learning as a function of interstimulus interval, primary and secondary excitatory and inhibitory conditioning, anticipatory conditioned responses, attentional focussing by conditioned motivational feedback, and limited capacity short term memory processing. Qualitative explanations are offered of why conditioned responses extinguish when a conditioned excitor is presented alone, but do not extinguish when a conditioned inhibitor is presented alone. These explanations invoke associative learning between sensory representations and drive, or emotional, representations (in the form of conditioned reinforcer and incentive motivational learning), between sensory representations and learned expectations of future sensory events, and between sensory representations and learned motor commands. Drive representations are organized in opponent positive and negative pairs (e.g., fear and relief), linked together by recurrent gated dipole, or READ, circuits. Cognitive modulation of conditioning is regulated by adaptive resonance theory, or ART, circuits which control the learning and matching of expectations, and the match-contingent reset of sensory short term memory. Dendritic spines are invoked to dissociate read-in and read-out of associative learning and to thereby design a memory which does not passively decay, does not saturate, and can be actively extinguished by opponent interactions.

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STEREO BOUNDARY FUSION BY CORTICAL COMPLEX CELLS: A SYSTEM OF MAPS, FILTERS, AND FEEDBACK NETWORKS FOR MULTIPLEXING DISTRIBUTED DATA

Stephen Grossberg† and Jonathan A. Marshall‡

Neural Networks, in press, 1989

ABSTRACT

A neural network model of multiple-scale binocular fusion and rivalry in visual cortex is described and simulated on the computer. The model consists of three parts: a distributed spatial representation of binocular input patterns among simple cells that are organized into ocular dominance columns; an adaptive filter from simple cells to complex cells; and a nonlinear on-center off-surround shunting feedback network that joins together the complex cells. This data structure generates complex cell receptive fields which multiplex input position, orientation, spatial frequency, positional disparity, and orientational disparity, and which are insensitive to direction-of-contrast in the image. Multiple copies of this circuit are replicated in the model using receptive fields of different sizes. Within each such circuit, the simple cell and complex cell receptive field sizes covary. Together these circuits define a self-similar multiple-scale network. The self-similarity property across spatial scales enables the network to exhibit a size-disparity correlation, whereby simultaneous binocular fusion and rivalry can occur among the spatial scales corresponding to a given retinal region. It is shown that a laminar organization of the model interactions among the complex cells gives rise to conceptually simple growth rules for intercellular connections. The output patterns of the model complex cells are designed to feed into the model hypercomplex cells at the first competitive stage of a Boundary Contour System network, where they trigger a process of multiple-scale emergent binocular boundary segmentation. The modelling results are compared with psychophysical data about binocular fusion and rivalry, as well as with the cepstrum stereo model of Yeshurun and Schwartz. The results indicate that analogous self-similar multiple-scale neural networks may be used to carry out data fusion of many other types of spatially organized data structures.

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NEURAL DYNAMICS OF SURFACE PERCEPTION: BOUNDARY WEBS, ILLUMINANTS, AND SHAPE-FROM-SHADING

Stephen Grossberg† and Ennio Mingolla‡

Computer Vision, Graphics, and Image Processing, 1987, **37**, 116–165

ABSTRACT

A real-time visual processing theory is used to provide a new approach to the analysis of surface perception, notably shape-from-shading. The theory has elsewhere been used to explain data about boundary detection and completion, textural segmentation, depth perception, color and brightness perception, and striate-prestriate cortical interactions. Neural network interactions within a multiple scale Boundary Contour (BC) System and Feature Contour (FC) System are used to explain these phenomena. Each spatial scale of the BC System contains a hierarchy of orientationally tuned interactions, which can be divided into two successive subsystems called the OC Filter and the CC Loop. The OC Filter contains two successive stages of oriented receptive fields which are sensitive to different properties of image contrasts. The OC Filter generates inputs to the CC Loop, which contains successive stages of spatially short-range competitive interactions and spatially long-range cooperative interactions. Feedback between the competitive and cooperative stages synthesizes a coherent, multiple scale structural representation of a smoothly shaded image, called a *boundary web*. Such a boundary web regulates multiple-scale filling-in reactions within the FC System which generate a percept of form-and-color-in-depth. Computer simulations establish key properties of a boundary web representation: nesting of boundary web reactions across spatial scales, coherent completion and regularization of boundary webs across incomplete image data, and relative insensitivity of boundary webs to illumination level and highlights. The theory clarifies data about interactions between brightness and depth percepts, transparency, influences of highlights on perceived surface glossiness, and shape-from-texture gradients. The total network suggests a new approach to the design of computer vision systems, and promises to provide a universal set of rules for 3-D perceptual grouping of scenic edges, textures, and smoothly shaded regions.

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NEURAL DYNAMICS OF ATTENTIONALLY-MODULATED PAVLOVIAN CONDITIONING: CONDITIONED REINFORCEMENT, INHIBITION, AND OPPONENT PROCESSING

Stephen Grossberg† and Nestor A. Schmajuk‡

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ABSTRACT

A real-time neural network model is developed to explain data about the acquisition and extinction of conditioned excitors and inhibitors. Systematic computer simulations are described of a READ circuit, which joins together a mechanism of associative learning with an opponent processing circuit, called a *recurrent gated dipole*. READ circuit properties clarify how positive and negative reinforcers are learned and extinguished during primary and secondary conditioning. Habituating chemical transmitters within a gated dipole determine an affective adaptation level, or context, against which later events are evaluated. Neutral CS's can become reinforcers by being associated either with direct activations or with antagonistic rebounds within a previously habituated dipole. Neural mechanisms are characterized whereby conditioning can be actively extinguished, and associative saturation prevented, by a process called *opponent extinction*, even if no passive memory decay occurs. Opponent extinction exploits a functional dissociation between read-in and read-out of associative memory, which may be achieved by locating the associative mechanism at dendritic spines. READ circuit mechanisms are joined to cognitive-emotional mechanisms for associative learning of conditioned reinforcers and of incentive motivation; and to cognitive, in particular adaptive resonance theory, mechanisms for activating and storing internal representations of sensory cues in a limited capacity short term memory (STM); for learning, matching, and mismatching sensory expectancies, leading to the enhancement or updating of STM; and for shifting the focus of attention towards sensory representations whose reinforcement history is consistent with momentary appetitive requirements. This total neural architecture is used to explain conditioning and extinction of a conditioned excitor; conditioning and non-extinction of a conditioned inhibitor; properties of conditioned inhibition as a "slave" process and as a "comparator" process, including effects of pretest deflation or inflation of the conditioning context, of familiar or novel training or test contexts, of weak or strong shocks, and of preconditioning US-alone exposures. The same mechanisms have elsewhere been used to explain phenomena such as blocking, unblocking, overshadowing, latent inhibition, superconditioning, inverted U in conditioning as a function of interstimlus interval, anticipatory conditioned responses, partial reinforcement acquisition effect, learned helplessness, and vicious-circle behavior. The theory clarifies why alternative models have been unable to explain an equally large data base.

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NEURAL DYNAMICS OF ADAPTIVE TIMING AND TEMPORAL DISCRIMINATION DURING ASSOCIATIVE LEARNING

Stephen Grossberg† and Nestor A. Schmajuk‡

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ABSTRACT

A neural network model that controls behavioral timing is described and simulated. This model, called the Spectral Timing Model, controls a type of timing whereby an animal or robot can learn to wait for an expected goal by discounting expected nonoccurrences of a goal object until the expected time of arrival of the goal. If the goal object does not then materialize, the animal can respond to unexpected nonoccurrences of the goal with appropriate changes in information processing and exploratory behavior. The model is a variant of the gated dipole model of opponent processing. When the gated dipole model is generalized to include a spectrum of cellular response rates within a large population of cells, the model's total output signal generates accurate learned timing properties that collectively provide a good quantitative fit to animal learning data. In particular, the Spectral Timing Model utilizes the habituative transmitter gates and adaptive long term memory traces that are characteristic of gated dipole models. The Spectral Timing Model is embedded into an Adaptive Resonance Theory (ART) neural architecture for the learning of correlations between internal representations of recognition codes and reinforcement codes. This type of learning is called conditioned reinforcer learning. The two types of internal representations are called sensory representations (S) and drive representations (D). Activation of a drive representation D by the Spectral Timing Model inhibits output signals from the orienting subsystem (A) of the ART architecture and activates a motor response. The inhibitory pathway helps to prevent spurious resets of short term memory, forgetting, and orienting responses from being caused by events other than the goal object prior to the expected arrival time of the goal. Simulated data properties include the inverted U in learning as a function of the interstimulus interval (ISI) that occurs between onset of the conditioned stimulus (CS) and the unconditioned stimulus (US); correlations of peak time, standard deviation, Weber fraction, and peak amplitude of the conditioned response as a function of the ISI; increase of conditioned response amplitude, but not its timing, with US intensity; speed-up of the timing circuit by an increase in CS intensity or by drugs that increase concentrations of brain dopamine or acetylcholine; multiple timing peaks in response to learning conditions using multiple ISI's; and conditioned timing of cell activation within the hippocampus and of the contingent negative variation (CNV) event-related potential. The results on speed-up by drugs that increase brain concentrations of dopamine and acetylcholine support a 1972 prediction that the gated dipole habituative transmitter is a catecholamine and its long term memory trace transmitter is acetylcholine. It is noted that the timing circuit described herein is only one of several functionally distinct neural circuits for governing different types of timed behavior competence.

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